

LINEAR OPTICAL SAMPLING METHOD AND APPARATUS

TECHNICAL FIELD OF THE INVENTION

5 This invention relates generally to linear optical sampling and, more particularly, to a linear optical sampling apparatus including a 90⁰ optical hybrid and a sample scaling processor.

BACKGROUND OF THE INVENTION

10 The temporal characterization of high bit-rate sources is crucial for the development of high-speed optical telecommunications. As direct photodetection and electronic sampling do not have the required bandwidth, such characterization must be performed by taking advantage of the large bandwidth of optical sources. A nonlinear
15 interaction with an ancillary pulse, such as sum-frequency generation, four-wave mixing, cross-phase modulation or two-photon absorption, can be used to provide a temporal gating mechanism with a resolution on the order of the duration of the ancillary pulse [1-5]. (Note, the bracketed references [] refer to publications listed in the attached Reference list.) Because sub-picosecond sampling pulses are available,
20 such an approach can lead to a detection bandwidth on the order of 500 GHz. However, it often lacks sensitivity. For example, sampling of eye diagrams at 640 Gb/s was achieved with a sensitivity equal to $1.3 \times 10^8 \text{ mW}^2$, stated as the product of the peak power of the sampling source and the peak power of the data source [5].

25 Linear optical sampling, where the electric field of the waveform under test is gated by the electric field of a sampling pulse, can demonstrate temporal resolutions identical to nonlinear techniques with a large gain in sensitivity. Using a free-space setup, sampling up to 80 Gb/s with sensitivity equal to 80 mW^2 was demonstrated [6].

30 Notwithstanding the demonstrated free-space linear optical sampling arrangement, there is a continuing need to implement a more practical linear optical sampling apparatus with improved performance.

SUMMARY OF THE INVENTION

5 In accordance with the present invention, we describe a linear optical sampling apparatus, which temporally characterizes a data modulated optical signal using the amplitude of the interference of its electric field with the electric field of a short laser pulse. The apparatus includes a 90° optical hybrid that produces the interference and generates two quadratures interference samples S_A and S_B formed as a result of the
10 interference. A processor compensates for optical and electrical signal handling imperfections in the hybrid, balanced detectors, and A/D converters used in the optical sampling apparatus. The processor numerically scales the two quadratures interference samples S_A and S_B over a large collection of samples by imposing that the average $\langle S_A \rangle = \langle S_B \rangle = 0$ and $\langle S_A^2 \rangle = \langle S_B^2 \rangle$ and then minimizes $2 \langle S_A \cdot S_B \rangle / (\langle S_A^2 \rangle + \langle S_B^2 \rangle) = \cos(\varphi_B - \varphi_A)$. This is done by adjusting the phase between the two
15 quadratures (ideally either $-\pi/2$ or $+\pi/2$) so that $\cos(\varphi_B - \varphi_A)$ is zero. The processor then generates a demodulated sample data pulse signal using the quadratures interference samples S_A and S_B .

 According to one feature, the hybrid combines the two sources and sets the
20 relative phase between two quadratures of their interferometric component so that the phase sensitivity inherent to linear optics is removed. In a preferred embodiment, the hybrid is implemented using integrated silica waveguide technology. Sampling of picosecond pulses and eye diagrams up to 640 Gb/s with high sensitivity and temporal resolution is demonstrated. Optimal time resolution and low distortion are obtained by
25 proper choice of the spectral characteristics of the sampling pulse.

 More specifically, our invention is a linear optical signal sampler apparatus for measuring temporal samples of a data modulated optical signal (DOS) 101, the linear optical signal sampler apparatus comprising

a pulsed optical signal (POS) 102 having the same polarization as the DOS and operable at a pulse rate equal to a fraction of the data modulation rate of the DOS;

5 a 90° hybrid having a first input for receiving the DOS and a second input for receiving the POS, the hybrid combining the DOS and POS to produce temporal quadrature samples S_A and S_B of the interference of the electrical fields of the DOS with the POS, the optical signals producing the S_A quadrature samples being outputted at a first and second outputs, and the optical signals producing the S_B quadrature samples being outputted at a third and fourth outputs;

10 two balanced photodetectors (BDA,BDB) 120, 121 operable at the pulse rate of the POS, coupled to the first, second, third, and fourth outputs for detecting and generating analog electrical signal representations of the S_A and S_B quadrature samples;

15 a sampling analog/digital (A/D) converter apparatus 130 for sampling and generating digital representations of the real and imaginary components of the S_A and S_B quadratures samples, the sampling A/D detector apparatus being synchronized to the pulses of the SOS; and

20 a processor for compensating for optical and electrical signal handling imperfections in the hybrid, balanced detectors, and A/D converters and for measuring temporal signal samples using quadratures samples S_A and S_B and then generating a demodulated sampled data pulse from the quadratures samples S_A and S_B .

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According to another feature of our invention, we describe a method of operating an optical signal sampler apparatus for measuring temporal samples of a data modulated optical signal (DOS) 101, comprising the steps of:

30 (1) receiving a data modulated optical signal (DOS);

(2) receiving a pulsed optical signal (POS) at a pulse rate equal to a fraction of the data modulation rate of the DOS;

(3) producing a S_A and a S_B quadratures samples of the interference of the electrical fields of the DOS with the POS;

5 (4) detecting and generating digital representations of the S_A and S_B quadratures samples;

(5) compensating for signal handling imperfections in the apparatus used to perform steps (3) and (4);

10 (6) measuring temporal signal samples by generating a demodulated sampled pulse from the quadratures samples S_A and S_B .

Another aspect of our invention is directed to an optical receiver for demodulating the data from a data modulated optical signal source (DOS) 101
15 received over an optical facility, the optical receiver comprising

a pulsed optical signal source (POS) 102, having the same polarization as the DOS, operable at a pulse rate equal to the data modulation rate of the DOS;

20 a 90° hybrid having a first input for receiving the DOS and a second input for receiving the POS, the hybrid combining the DOS and POS to produce quadratures samples S_A and S_B of the interference of the electrical fields of the DOS with the POS, the signals producing the S_A quadrature samples being outputted at a first and second outputs, and the optical signals producing the S_B quadrature samples being outputted
25 at a third and fourth outputs;

a first balanced photodetector (BDA) 120, operable at the data modulation rate of the DOS, coupled to the first and second outputs for detecting and generating analog electrical signal representations of the S_A quadrature samples;

a second balanced detector BDB 121, operable at the data modulation rate of the DOS, coupled to the third and fourth outputs for detecting and generating analog electrical signal representations of the S_B quadrature samples;

- 5 a sampling analog/digital (A/D) converter apparatus 130 for sampling and generating digital representations of the S_A and S_B quadratures samples, the sampling A/D detector apparatus being synchronized to the pulses of the SOS; and

- 10 a processor apparatus for processing the two quadratures samples S_A and S_B and for generating therefrom a demodulated sample data output.

Other features describe a variety of hybrid arrangements for use in the optical signal sampler apparatus.

15 **BRIEF DESCRIPTION OF THE DRAWINGS**

The present invention will be more fully appreciated by consideration of the following Detailed Description, which should be read in light of the accompanying drawing in which:

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Fig. 1 illustrates a generalized block diagram of our linear optical signal sampler apparatus.

- 25 Fig. 2 illustrates, in accordance with the present invention, a preferred embodiment of the hybrid shown in Fig. 1.

Fig. 3 shows illustrative signals of the data source, pulse source, and data output for the linear optical signal sampler apparatus.

Fig. 4 illustrates, in accordance with the present invention, the preferred operating functions performed by the processor.

Figs. 5(A), 5(B), and 5(C) illustrate the outputs of balanced detectors BDA and BDB around the peak of the waveform measured for values of the relative phase $\varphi_B - \varphi_A$ equal to 0, $\pm\pi/2$ and π .

Figs 6-10 illustrate, in accordance with the present invention, alternate arrangements of linear optical samplers.

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Fig. 11 illustrates an implementation of our invention as an optical receiver.

In the following description, identical element designations in different figures represent identical elements. Additionally in the element designations, the first digit refers to the figure in which that element is first located (e.g., 101 is first located in Fig. 1).

DETAILED DESCRIPTION

1. Linear optical sampling

The following paragraphs summarize the linear optical sampling apparatus described in reference [6] which is incorporated by reference herein. Linear optical sampling temporally characterizes an optical waveform by measuring the amplitude of the interference of its electric field $E_D(t)$ with the electric field of a sampling pulse $E_S(t)$ using two orthogonal quadratures of the interference. A quadrature $S_A = \text{real} \left[\exp(i\varphi_A) \cdot \int E_D(t) \cdot E_S^*(t) dt \right]$ can be obtained by combining the two sources optically and performing time-integrated balanced detection on the two outputs of the coupler using low-speed detectors (the temporal integration extends in theory only over the integration time of the detectors, but such time is in practice much longer than the durations of the various pulses, and integration will always be taken from $-\infty$ to $+\infty$ for the sake of simplicity). The constant phase φ_A describes the optical phase

difference between the two fields, and makes the value of a single quadrature highly dependent upon the delay between the two sources. Such dependence is removed by simultaneously measuring an orthogonal

quadrature $S_B = \text{real} \left[\exp(i\varphi_B) \cdot \int E_D(t) \cdot E_S^*(t) dt \right]$, with $\varphi_B - \varphi_A = \pm\pi/2$. The two

5 quadratures can be squared and summed to give $\left| \int E_D(t) \cdot E_S^*(t) dt \right|^2$. In practice, the sampling pulse scans through the waveform to be characterized because of the offset in the rate of the two sources, so that the acquired samples are

$$S(\tau) = \left| \int E_D(t) \cdot E_S^*(t - \tau) dt \right|^2 \quad (1)$$

This convolution can be written in the frequency domain as:

$$10 \quad S(\tau) = \left| \int E_D(\omega) \cdot E_S^*(\omega) \cdot \exp(i\omega\tau) d\omega \right|^2 \quad (2)$$

For a sampling pulse with constant spectral density and phase over the spectral support of the waveform under test, Eq. 2 leads to $S(\tau) = |E_D(\tau)|^2$, i.e. the temporal intensity of the waveform is measured without any blurring due to limited time resolution.

With reference to Fig. 1, in accordance with the present invention, we have
 15 recognized that a processor 140 can be used for compensating for optical and electrical signal handling imperfections in the hybrid (such as unequal splitting and combining ratios of the optical sources), balanced detectors (such as unequal gains of the detectors and electrical amplifiers), and A/D converters (such as unequal gains of the electronic circuits or imperfect synchronization of the circuits) used in the optical
 20 sampling apparatus to compensate for non-optimal implementation. The processor 140 does this by making numerical scaling adjustments in the temporal quadrature samples S_A and S_B . Since the data source 101, pulse optical source 102 are not correlated, the two quadratures should have an average value equal to zero and identical variances. Numerically scaling the two measured quadratures on a large
 25 collection of samples by imposing $\langle S_A \rangle = \langle S_B \rangle = 0$ and $\langle S_A^2 \rangle = \langle S_B^2 \rangle$ allows the compensation of non-perfect balanced detection. It can also be shown that $2\langle S_A \cdot S_B \rangle / (\langle S_A^2 \rangle + \langle S_B^2 \rangle)$ is equal to $\cos(\varphi_B - \varphi_A)$. Therefore, the phase (141) between

the two quadratures (ideally either $-\pi/2$ or $+\pi/2$) must be set in order to cancel such quantity. As will be discussed in detail in later paragraphs, the processor 140 of our linear optical signal sampler apparatus numerically scales the two quadratures interference samples S_A and S_B over a large collection of samples by imposing $\langle S_A \rangle = \langle S_B \rangle = 0$ and $\langle S_A^2 \rangle = \langle S_B^2 \rangle$ and then minimizes $2 \langle S_A \cdot S_B \rangle / (\langle S_A^2 \rangle + \langle S_B^2 \rangle) = \cos(\varphi_B - \varphi_A)$. This is done by adjusting the phase between the two quadratures (ideally either $-\pi/2$ or $+\pi/2$) so that $\cos(\varphi_B - \varphi_A)$ is zero. The processor 140 then generates a demodulated sample data pulse signal using the quadratures interference samples S_A and S_B , for example, by calculating the sum $S_A^2 + S_B^2$.

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2. Improved linear optical signal sampler apparatus

The following description jointly references Fig. 1 and Fig.3. Figure 1 illustrates a generalized block diagram of our linear optical signal sampler apparatus. Figure 3 shows illustrative signals of data source 101, pulse optical source 102, and demodulated sample data pulse signal 142. As shown in Fig. 1, the data source (or source under test) 101 connects to a first input port of a 90° optical hybrid 110. The signal from data source 101 is typically a data modulated optical carrier signal - shown by 101 in Fig. 3. A pulse optical source 102 (typically a sampling or pulsed laser signal - shown by 102 of Fig.3) connects to a second input port of 90° optical hybrid 110. The data source 101 and pulse optical source 102 have the same polarization. The optical hybrid 110 may be implemented using one hybrid (see Figs. 2, 6, 9, and 10) or using two hybrids (see Figs. 7 and 8). Depending on the configuration, either two balanced detectors (e.g., BDA, BDB of Fig. 2) or four balanced detectors (e.g., BDA, BDB and BDC, BDD of Fig. 7) are used in balance detector unit 120. The A/D unit 130 is selected to be compatible with balanced detector unit 120, so as to be able to process the outputs from the one or two set of balanced detectors.

In hybrid 110, the short laser pulse of pulse optical source 102 temporally characterizes the data modulated optical signal of data source 101 using the amplitude of the interference of its electric field with the electric field of the short laser pulse. The spectral characteristics of the pulse optical source 102 is selected to spectrally

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overlap pulses of data source 101 to provide optimal time resolution and low distortion in the demodulated sample data pulse signal 142.

A portion of the pulse optical source 102 is also coupled, via coupler 103, to provide a trigger signal to synchronize the operation of analog to digital (A/D) circuit 130. In an alternate arrangement (shown in dotted-lines in Fig. 1), a clock signal 143 (for example, in the RF domain) from the processor 140 is used to set the sampling rate of sampling laser 102 and the sampling rate of A/D circuit 130.

The 90° optical hybrid 110 produces the interference of the data source 101 electric field with the electric field of pulsed laser signal 102 resulting in the generation of two quadratures interference samples S_A and S_B . The two quadratures interference samples S_A and S_B are measured with two balanced photodetectors (BDA and BDB) 121 and 122, whose outputs are sampled by the two ports of an A/D board. The simultaneous acquisition of the two quadratures S_A and S_B is synchronized to the pulsed laser signal 102.

In accordance with the present invention, the processor 140 compensates for signal processing imperfections in the hybrid unit 110, balanced detector unit 120, and A/D converters 130 and measures temporal signal samples using quadratures samples S_A and S_B . The processor 140 then generates a demodulated sampled data pulse from the quadratures samples S_A and S_B (for example by generating a demodulated sampled data pulse having a power equal to the sum $S_A^2 + S_B^2$). The processor compensates for the signal processing imperfections by numerically scaling quadratures samples S_A and S_B over a large collection of samples by imposing that the average $\langle S_A \rangle = \langle S_B \rangle = 0$ and $\langle S_A^2 \rangle = \langle S_B^2 \rangle$. The processor compensates for the signal processing imperfections by controlling the relative phase between quadratures samples S_A and S_B and by ensuring that $2 \langle S_A \cdot S_B \rangle / (\langle S_A^2 \rangle + \langle S_B^2 \rangle)$ is equal to zero by adjusting the phase of quadratures samples S_A and S_B in the hybrid or by numerical processing of quadratures samples S_A and S_B .

More specifically, processor 140 performs adjustment of the mean and standard deviation of the two quadratures S_A and S_B , and the squaring and summing to generate the demodulated sample data pulse signal 142 (shown by 142 in Fig. 3). The

processor 140 performs these adjustments by controlling the phase between the two quadratures S_A and S_B using phase control signal 141.

The operations performed by the processor 140 are shown illustratively in Fig. 4. As shown in Fig. 4, processor 140

- 5 - A. Numerically scales the two quadratures interference samples S_A and S_B over a large collection of samples by imposing that $\langle S_A \rangle = \langle S_B \rangle = 0$ and $\langle S_A^2 \rangle = \langle S_B^2 \rangle$, where the brackets represent the average value calculated over a large number of samples. This can be achieved by:
 - a. Calculating $\langle S_A \rangle$, then calculating $S_A' = S_A - \langle S_A \rangle$ and using it for all subsequent operations.
 - 10 - b. Calculating $\langle S_B \rangle$, then calculating $S_B' = S_B - \langle S_B \rangle$ and using it for all subsequent operations.
 - c. Calculating $\sigma_A'^2 = \langle S_A'^2 \rangle$, then calculating $\sigma_B'^2 = \langle S_B'^2 \rangle$, then defining S_A'' and S_B'' such as $S_A'' = S_A' / \sigma_A'$ and $S_B'' = S_B' / \sigma_B'$. Note that other scalings techniques can be performed (what matters in the end is that the standard variation calculated on the two quadratures are identical).
- 15 B. Calculates the quantity $2 \langle S_A'' \cdot S_B'' \rangle / (\langle S_A''^2 \rangle + \langle S_B''^2 \rangle)$, which is equal to the cosine of the relative phase between the two quadratures [i.e., $\cos(\varphi_B - \varphi_A)$]. As the relative phase should be equal to either $+\pi/2$ or $-\pi/2$ for optimal operation, its cosine should be equal to 0.
- 20 C. Adjusts the relative phase between the two quadratures so that the calculated $2 \langle S_A'' \cdot S_B'' \rangle / (\langle S_A''^2 \rangle + \langle S_B''^2 \rangle)$ is close to zero, within experimental uncertainty. With the hybrid, this operation is performed by the processor 140 adjusting, via phase adjust control signal 141, the voltage applied to the phase-shifter (212 of Fig. 2).
- 25 D. The processor then generates a demodulated sample data pulse signal 142 equal to the sum $S_A''^2 + S_B''^2$.

30 Using our linear optical signal sampler apparatus of Fig. 1, including the novel processor 140 functions, enable the demodulation of 1.2 ps (pico second) data pulses

that have been data-modulated at up to the 640Gb/s (301 of Fig. 3) using a 1.2 ps pulsed laser signal (302 of Fig. 3) that has the same polarization as the modulated data signal. The output of our linear optical signal sampler apparatus (142 of Fig. 3) is a demodulated sampled 640 Gb/s data signal, or eye diagram signal, which is achieved with about a 10^3 improvement in sensitivity and with almost no distortion. The processor 140 may be implemented using one or more technologies including hardware, firmware, and software that are arranged to perform the above described operations.

10 **3. Preferred Linear Optical Sampler**

With reference to fig. 2, we describe a preferred implementation of linear optical sampling apparatus based on an integrated optical hybrid, with a large gain in practicality compared to the free-space setup previously demonstrated [6]. As can be seen on Fig. 2, the hybrid 110 accepts the fields of the sampling laser 102 and source under test 101 (whose polarizations have been made identical using a polarization controller PC 201) as two inputs and provides two pairs of combined fields (two quadratures S_A and S_B) as four outputs. The hybrid structure is made of silica waveguides on a silicon substrate. It will be appreciated by those skilled in the art that other planar lightwave structures, such as InP waveguides, could be built to produce essentially the same function. While for clarity the layout of the hybrid on Fig. 2 was stretched vertically, the actual physical size of the structure is about 1.6 cm (from top to bottom) by 4.0 cm (from left to right). The two interference couplers 213 and 214, shown illustratively as 2-by-2 three-section couplers, provide 3 dB coupling with low wavelength, polarization and fabrication sensitivity [7]. The phase difference between the two quadratures S_A and S_B is set using a thermo-optic phase shifter 212 in one section of the hybrid 110; a voltage V , illustratively 3 volts, corresponds approximately to a phase shift of one radian. The precise control (using phase adjust 141) of the relative phase results in polarization and wavelength insensitivity making our hybrid desirable compared to previously realized hybrids [8-9].

30 Further simplification of the arrangement of Fig. 2 is possible by monolithic integration of the balanced detectors 120 with the hybrid 110 [10]. Illustratively, a 10

MHz passively mode-locked fiber laser is used as the sampling laser 102. As detailed below, the laser (which has a bandwidth of the order of 40 nm) is filtered 202 in order to match the spectral support of the data source under test 101, since only the energy of the sampling laser pulse 102 spectrally overlapping with the source under test 101 contributes to the signal. The two quadratures S_A and S_B are measured, illustratively, using two 700-MHz balanced photodetectors (BDA and BDB) whose outputs are sampled by the two ports of an A/D unit 130. The simultaneous acquisition of the two quadratures S_A and S_B is synchronized to the sampling pulses using a low-speed photodiode and pulser 131. As noted previously, processor 140 uses phase adjust signal 141 to perform scaling adjustments of the mean and standard deviation of the two quadratures S_A and S_B . Processor 140 then performs the squaring and summing to generate the demodulated sample data pulse signal 142.

Illustrative tests on the linear optical sampling apparatus of Fig. 2, produced a connector-to-connector input-to-output losses measured using a non-polarized source range from 9.5 dB to 10.1 dB, including 6 dB corresponding to the power splitting (by 3-dB couplers 210, 211). The polarization dependence of the input-to-output transmission was measured as 0.6 dB. The ability of the optical hybrid 110 to precisely set the phase between the two quadratures is demonstrated when sampling a 10 GHz 33 % return-to-zero waveform (without data encoding).

A detail of the two signals measured by the balanced detectors BDA and BDB (continuous and dashed line, respectively) around the peak of the waveform measured for values of the relative phase $\varphi_B - \varphi_A$ equal to 0, $\pm\pi/2$ and π is plotted, respectively, as (A), (B), and (C) on Fig. 5 [where the vertical axis is measured in arbitrary units (a.u.), and the horizontal axis corresponds to sampling events] .

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4. Alternative Linear Optical Samplers

For ease of comparison between the linear optical samplers of Figs. 6-10, the 90° optical hybrid 110 of Fig. 1 has been redrawn as shown in Fig. 6, with the positions of the data source 101 (source under test) and sampling laser (pulsed source) 102 reversed. Waveguide structures, 1:2 couplers (3-dB) 601, 602, are used to split the data source (E_D) 101 and sampling source (E_S) 102, respectively, and interference

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couplers 603 and 604 are used to recombine the sources and set the relative phase between the two quadratures. The elements 601 – 604 essentially form a hybrid 600 similar to hybrid 110 of Fig. 2. The two sources E_D and E_S are copolarized. The phase difference between the two quadratures S_A and S_B is set using a thermo-optic phase shifter 212. Note that while thermo-optic phase shifter 212 has been shown in path 613, it could also have been placed in any of the other paths 611, 612, and 614.

The two quadratures S_A and S_B are measured with two balanced detectors BDA and BDB, respectively. The processor 140 then operates on the quadrature pair (S_A , S_B). Such an implementation can only sample the portion of the source under test E_D that is copolarized with the sampling laser E_S . However, in real applications, the polarization of the source under test E_D is unknown and can vary significantly and rapidly. Therefore we must characterize the source under test E_D at a given time along its two polarizations, which can be referred to as polarization diversity. The total intensity of the source under test E_D (as would be measured by a conventional photodetector if such a detector with suitable bandwidth is available) is the sum of the intensities of each polarization. Polarizers and half-wave plate can be built using waveguide technology. For example, a polarizer can be implemented using a Mach-Zehnder interferometer with a birefringent element in one of its arms. A half-wave plate can be implemented using a birefringent element integrated to the waveguide.

In Fig. 7, the source under test E_D is split by a polarizer 701, the sampling pulse E_S is split with a polarizer 702, and two pair of hybrids 710, 711 and 712, 713 are used to sample each of the polarizations of the source under test with a copolarized sampling pulse. Note that while the thermo-optic phase shifter 212 is shown in Fig. 7 as located in a particular path of each hybrid 703 and 704, it may alternatively be located in any of the other paths in the same manner as discussed previously for Fig. 6. Similarly in Figs. 8 – 10 the thermo-optic phase shifter 212 can be located in any of the paths.

Returning to Fig. 7, the two quadratures for one polarization “x” of the source under test are measured with BDA and BDB, while the two quadratures for the other polarization “y” are measured with BDC and BDD. The processor 140 then operates

independently, as described previously, on the quadrature pairs (S_A, S_B) and (S_C, S_D) to generate the demodulated sample data signal 142.

In Fig. 8, the source under test E_D is split by a polarizer 801 into its polarization x and y. The sampling pulse E_S linearly polarized along x is split with a 3-dB coupler (splitter) 802, therefore generating two sampling pulses with polarization x. The x polarization of the source under test E_D goes to the first hybrid 810, and is sampled by the sampling pulse E_S . The y polarization of the source under test E_D goes to the second hybrid coupler 820. The polarization of the sampling pulse is rotated by a half-wave plate 803 and becomes y, and the subsequent sampling pulse is sent to the second hybrid coupler 820. The x polarization of the source under test E_D is therefore obtained from the balanced detectors BDA and BDB, while the y polarization of the source under test is obtained from the balanced detectors BDC and BDD. Note that one could also choose to rotate the polarization of the source under test E_D in the second interference coupler 820, instead of rotating the polarization of the sampling pulse E_S . The processor 140 then operates independently, as described previously, on the pair (S_A, S_B) and on the pair (S_C, S_D).

In Fig. 9, a sampling pulse E_S with energy along the two polarizations x and y is sent into a single hybrid 600 with the source under test E_D of unknown state of polarization. At the 4 outputs of hybrid 600, polarizers 911 – 914 are set in order to split the recombined fields into linear polarizations along x and y. In this embodiment, the x polarization of the source under test is obtained from the 2 balanced detectors BDA and BDC, while the y polarization is obtained from the 2 balanced detectors BDB and BDD. Again as described previously, processor 140 operates independently on the pair (S_A, S_C) and on the pair (S_B, S_D).

In Fig. 10, the source under test E_D is sent into a delay box 1001 that splits it into its two orthogonal polarizations x and y, and introduces a relative delay T between them. The sampling pulse is sent to an identical delay box 1002, which generates two sampling pulses polarized along x and y, with a relative delay T. The two sources are sent into a single interference coupler 1010. The signals that are

measured by the two balanced detectors BDA, BDB for the first and second sampling pulses generated by the delay box 1002 correspond to the quadratures of the interference of the source under test along its two polarizations S_{Ax} , S_{Bx} and S_{Ay} , S_{By} . The processor then operates independently, as described previously, on the pair (S_{Ax} , S_{Bx}) and on the pair (S_{Ay} , S_{By}).

5. Optical Receiver

Shown in Fig. 11 is an implementation of our invention as an optical receiver for demodulating a data modulated optical signal (DOS) 1101 received over an optical facility. As shown DOS 1101 is coupled to a first input port of a 90° optical hybrid 1110. A pulse optical source 1102 (pulsed laser signal) having the same data (or pulse) rate and polarization as DOS 1101, connects to a second input port of 90° optical hybrid 1110. As previously discussed with reference to Fig. 1, the optical hybrid 1110 may be implemented using one hybrid (see Figs. 2, 6, 9, and 10) or using two hybrids (see Figs. 7 and 8). Depending on the configuration, two balanced detectors (e.g., BDA, BDB of Fig. 2) or four balanced detectors (e.g., BDA, BDB and BDC, BDD of Fig. 7) are used in balance detector unit 1120. The A/D unit 1130 is selected to be compatible with balanced detector unit 1120, so as to be able to process the outputs from the one or two set of balanced detectors. For convenience, the receiver of Fig. 11 is assumed to use one hybrid in hybrid unit 1110, one set of balanced detectors in balanced detector unit 1120, and an compatible A/D unit 1130.

A portion of the pulse optical source 1102 is coupled, via coupler 103, to provide a trigger signal to synchronize the operation of analog/digital (A/D) circuit 1103. In an alternate arrangement (shown in dotted-lines in Fig. 11), a clock signal 1151 (for example, in the RF domain) from the processor 1140 is used to set the sampling rate of pulsed source 1102 and the sampling rate of A/D circuit 1130.

The 90° optical hybrid 1110 produces an interference of the electric field of DOS 1101 with the electric field of pulsed laser signal 1102 resulting in the generation of two quadratures interference samples S_A and S_B . The two quadratures interference

samples S_A and S_B are measured with two high speed balanced photodetectors (BDA and BDB) 1102, which operate at the data rate of DOS 1101. Illustratively, the two high speed balanced photodetectors 1102 may be implemented using silicon or InGaAs. The outputs of BDA and BDB, 1102, are sampled by the two ports of an A/D board 1103. The A/D circuit 1103 is arranged to operate at the data rate of DOS 1001, so as to be able to generate digital samples of the quadratures interference samples S_A and S_B . Illustratively, the A/D circuit 1103 may contain sample-and-hold circuits that are commonly used in telecommunication systems. In the same manner as discussed with reference to Fig. 1, the processor 1104 is arranged to calculate a demodulated sample data signal 1105 having an power level equal to the sum $S_A^2 + S_B^2$. Since the pulse optical source 1102, BDA and BDB, 1102, A/D board 1103, and processor 1104 all operate at input data modulated optical signal (DOS) 1101 rate, the demodulated output signal 1105 is at the data rate of DOS 1101. The data transmission rate of the receiver of Fig. 11 is limited by the bandwidth of the two high speed balanced photodetectors (BDA and BDB) 1102.

Various modifications of our invention will occur to those skilled in the art. Nevertheless all deviations from the specific teachings of this specification that basically rely upon the principles and their equivalents through which the art has been advanced are properly considered within the scope of the invention as described and claimed.

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